NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3746

INITIAL RESULTS OF A FLIGHT INVESTIGATION OF THE WING AND TAIL LOADS ON AN AIRPLANE EQUIPPED WITH A VANE-CONTROLLED GUST-ALLEVIATION SYSTEM

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Washington

September 1956

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SUMMARY

A flight investigation has been made of wing and horizontal-tail loads and spar strains on a twin-engine light transport airplane which was modified for the installation of a control system that would alleviate airplane motions in turbulent air and thus improve passenger comfort. In the control system used, changes in the angle of attack produced by gusts were sensed by a vane which causes the trailing-edge flaps and ailerons to deflect in order to counteract lift. The elevator was split and the outer parts were geared to the flaps to balance pitching moment.

The results presented are from an initial analysis of a sample of the measurements obtained in flight through clear-air turbulence with the control system on and off and represent the initial evaluation of the gust-alleviation-system effectiveness, not necessarily the optimum that can be obtained. There were indications that a reduction of 43 percent in root-mean-square normal acceleration at the airplane center of gravity was accomplished. This reduction in normal acceleration was accompanied by a reduction in main-spar bending strains of the wing; however, shear strains in both the main and rear spars of the test-airplane wing were increased because of operation of the trailing-edge flaps in the alleviated airplane configuration. Horizontal-tail shear and bending strains were increased because of operation of the split elevator on the gust-alleviated airplane. Increases in the magnitude and frequency of occurrence of some of the strains in the wing and tail structure in rough air which are associated with operation of the alleviation controls indicate that fatigue would be an important consideration in designs utilizing this type of gust-alleviation system. Measurements of wing and horizontal-tail aerodynamic loads obtained in a pull-up maneuver in smooth air with the system on and off are also presented.

INTRODUCTION

The National Advisory Committee for Aeronautics is currently conducting a flight investigation to determine the effectiveness of a vane-controlled gust-alleviation system. The aim of this investigation is to reduce the airplane response in the frequency range (0 to 2 cycles per second) in which it has been found that passengers are most sensitive to airplane motions. Thus, the control system was designed primarily to reduce airplane vertical accelerations and thereby improve passenger comfort.

A twin-engine light transport airplane was modified for the installation of the alleviation system, and research instrumentation was installed for evaluation of the system in flight. A description of the gust-alleviation control system and some initial results of the effectiveness of the system in reducing airplane motions are presented in reference 1.

When the control system is used, the additional lift produced by a gust is not eliminated at its source but is counteracted by a change in lift produced by the flap and elevator deflection. Since the distributions of the two opposing lifts are not identical, operation of the system must be expected to alter the distribution of strains in the structure.

The objective of the present investigation was to monitor the strains during the initial trials of the gust-alleviation system in order to get a better idea of the magnitude and importance of the expected changes in strain distribution. The loads and strain measurements for the basic airplane and the airplane with the gust-alleviation system in operation were determined and compared, and an analysis of these initial results is presented in this report.

SYMBOLS

V true airspeed, ft/sec or knots as indicated

G_{WR} aerodynamic shear at wing-root strain-gage reference, lb

M_{WR} aerodynamic bending moment at wing-root strain-gage reference, in-lb

Q_{WR} aerodynamic torque at wing root about torque axis, in-lb

G_{TR}	aerodynamic shear on right horizontal tail at strain-gage reference, lb
a_n	normal acceleration at airplane center of gravity, g units
δ_f	wing flap deflection, deg
α	angle of attack, deg
α_t	average angle of attack over horizontal tail, deg
α_v	angle of attack indicated by vane, deg
α_v'	angle of attack measured at vane, corrected for pitching of airplane, $\alpha_v - \frac{l}{V}\dot{\theta}$, deg
l	distance from vane to airplane center of gravity, ft
l_t	distance from airplane center of gravity to quarter chord of horizontal tail, ft
$\dot{\theta}$	pitching velocity, radians/sec
δ_e	elevator deflection, deg
$\delta_{e,aux}$	auxiliary elevator deflection, deg
σ	root mean square or standard deviation
$\sigma_{\alpha,v}$	uncorrected angle of attack of vane, deg
e_s	standard error of estimate of coefficients in least-squares solution of linear-regression equations (see ref. 3 for method of evaluation)
g	acceleration due to gravity, ft/sec^2
Δ	represents an incremental value when used in conjunction with a symbol
ϵ	downwash angle at tail, deg

AIRPLANE AND INSTRUMENTATION

Airplane

A plan view of the test airplane showing the approximate locations of the strain-gage bridges is presented in figure 1, and some details of the wing structure are given in the cutaway sketch of the wing in figure 2.

For the present investigation, the original control surfaces of the airplane were modified in such a way that a portion of the landing flaps and ailerons was made to operate as a gust-alleviation control. The controls covered each wing semispan from 25 percent to 93 percent and were automatically actuated by the vane to move up or down to counteract lift changes due to gusts as well as to move differentially for lateral control when the gust-alleviation system was in operation. The original elevator was also modified in such a way that it consisted of a center elevator for maneuvering the airplane and two outer auxiliary elevators which moved in conjunction with the wing flaps to counteract the pitching moment due to flap deflection. The gust-alleviation controls are shown in the photographs of the airplane in figure 3. A more complete description of the alleviation system is given in reference 1. The airplane's physical characteristics (with the control-surface areas rearward of the hinge line) are presented in the following table:

Weight, lb	9,400
Wing area, sq ft	349
Wing mean aerodynamic chord, ft	8.05
Total wing-flap area (alleviation control), sq ft	35.4
Horizontal-tail area, sq ft	65.4
Main-elevator area, sq ft	11.8
Total auxiliary-elevator area, sq ft	10.7
Tail length, ft	22.5
Distance from angle-of-attack vane to center of gravity, ft	15.1
Center-of-gravity position, percent of wing mean aerodynamic chord	26

Instrumentation

Standard NACA instruments were installed in the test airplane for the measurement of airspeed, altitude, pitching velocity, pitching acceleration, and normal acceleration at the airplane center of gravity and for normal acceleration at the tail. Control-position transmitters were located on each moveable control surface to give a continuous record of the position of the controls.

A vane for measurement of angle of attack was mounted on a boom extending forward of the nose of the fuselage (approximately 15 feet from the center of gravity of the airplane). This angle-of-attack vane was responsible both for transmitting the signal which activated the gust-alleviation controls and for measuring the angle of attack.

Airspeed was measured by using a standard NACA airspeed recorder connected to the airplane airspeed system. Calibrations have indicated that this airspeed system indicates negligible position error in the speed range covered in the present tests; therefore, no corrections have been made to the airspeed measurements.

Strain-gage bridges were installed on the front and rear spars of the right wing near the root and at a station approximately 39 percent of the semispan outboard of the airplane center line. The root gage station was approximately 3 inches outboard of the fuselage side, whereas the outboard station was approximately 12 inches outboard of the attachment point of the outer panel of the wing. Additional strain-gage bridges were installed on the horizontal-tail spars at a station approximately 13 inches from the fuselage center line.

A strain-gage calibration procedure was followed which was similar to that described in reference 2 and resulted in relationships among the various strain-gage-bridge outputs from which wing structural shear, bending moment, and torque and horizontal-tail structural shear and bending moment could be evaluated. The structural loads obtained from the flight measurements were converted to aerodynamic loads by means of an inertia correction equal to the weight (and moment of the weight) outboard of the strain-gage station multiplied by the normal acceleration at the surface.

Continuous time histories of all measurements were obtained and all records were correlated by the use of a 1/10-second time pulse.

RESULTS AND DISCUSSION

A comparison of the strain measurements for the test airplane flying in rough air with and without the alleviation system engaged was examined, and the effects on wing and tail structure of the operation of the alleviation controls were assessed.

With the alleviation system in operation, the trailing-edge wing flaps and auxiliary elevator responded to the pilot's control as well as to the angle-of-attack vane to provide the pilot with adequate longitudinal control. This method of longitudinal control resulted in a faster response in a pull-up maneuver than the basic airplane response. Therefore, aerodynamic loads in pull-ups with the basic airplane and with the alleviation system in operation are presented and analyzed.

Rough Air

Several tests were made through clear-air turbulence with the gust-alleviation system alternately on and off. In this report, two of these tests were selected for further study, one for the basic airplane and one with the alleviation system in operation. The results presented represent the initial attempt at selection of proper gear ratios between the various surfaces; further tests with the other configurations available may result in improved alleviation of normal acceleration and pitching moment and in changes in magnitude of loads. A portion of the oscillogram for each test is presented in figure 4 to illustrate variations in normal acceleration, control deflections, and strains. Both tests were made at an altitude of 3,000 feet at 130 knots true airspeed, the ratio of wing-flap deflection to angle-of-attack-vane deflection was set at -5.2, and the ratio of auxiliary-elevator deflection to wing-flap deflection was set at -0.45. The airplane center-of-gravity location for these tests was at approximately 26 percent mean aerodynamic chord.

An analysis was performed on a 40-second portion of each of the two tests in which the rough air was of essentially the same intensity $\left(\sigma_{\alpha,v} = 1.2^{\circ}\text{ or approximately 4 feet per second}\right)$ as indicated by the angle-of-attack-vane output. For this analysis, the normal acceleration of the airplane center of gravity and the output of each of the strain-gage bridges on the front and rear spars of the right wing and on the right horizontal tail were determined at 1/20-second intervals during the 40-second portion of each test. The resulting 800 points for each of the acceleration and strain measurements were then grouped into class intervals and the standard deviations of the grouped data were calculated. The desired comparison of the acceleration and strain increments for the basic and gust-alleviation airplane configurations was then made on the basis of the calculated standard deviations. The standard deviation, in addition to indicating the variability of the observations for each airplane configuration, gives additional information about the data. For instance, the maximum strain or normal acceleration experienced can be expected to be of the order of three times the standard deviation if it is assumed that the data are reasonably close to a normal or Gaussian distribution, since, for normal frequency distributions, approximately 99.7 percent of the data fall within a range of three standard deviations.

Normal acceleration.- A standard deviation of 0.102g was obtained for the basic airplane in turbulence as compared with 0.058g for the gust-alleviated airplane. If it is assumed, then, that the gust inputs are the same, a decrease of approximately 43 percent in the root-mean-square value of normal acceleration at the center of gravity is brought about by the alleviation system employed. A graphical illustration of the alleviation effect on normal acceleration is given by the histogram in figure 5. In this figure, the solid lines represent accelerations experienced by the basic airplane and the shaded lines represent the accelerations experienced by the alleviated airplane in rough air of approximately the same turbulence intensity. It will be noted that, for 42 of the 800 observations for the basic airplane, the accelerations of the center of gravity exceeded 0.175g; whereas no accelerations of this magnitude were experienced by the alleviated airplane.

Wing strains.- The strain indications obtained from the output of the individual strain-gage bridges were grouped into class intervals and the standard deviations were computed. A histogram of the strains experienced by the bending gages on the front spar at the wing root is presented in figure 6 to illustrate the changes in bending-strain levels associated with the basic and alleviated airplane configurations.

Histograms of shear-strain measurements at the outer strain-gage station of the wings are presented in figure 7. The magnitude of one standard deviation is indicated in figures 5 to 8 for each condition. A summary of the results presented in these figures as well as the results for all the strain-gage measurements on the wing are given in the following table. The calculated standard deviations in units of strain for each condition are given and the percent of alleviation or percent of increase of strain is indicated.

Strain-gage location on wing	Standard deviation (strain units)		Percent of change
	Basic	Alleviated	
Root main-spar bending . .	45.2	36.8	-19
Root main-spar shear . . .	12.9	18.6	44
Root rear-spar shear . . .	8.3	5.8	-30
Outer main-spar bending . .	42.5	35.0	-18
Outer main-spar shear . . .	36.8	27.0	-27
Outer rear-spar shear . . .	12.9	49.2	281

It is evident upon examination of the results presented in the previous table that the increases in strain which are introduced into the rear spar of the outer portion of the wing by motion of the trailing-edge flaps do not appear in the wing's rear spar at the root. The shear bridge on the main spar at the root, however, shows an increase in shear strain which indicates that shear is transferred to the main spar to be carried into the fuselage. The increase in main-spar strain results from the fact that the test airplane was essentially of single-spar construction, the rear spar not being continuous through the fuselage. For the wing of the test airplane, then, with 43 percent alleviation of center-of-gravity normal acceleration, the root main-spar bending strains were reduced approximately 20 percent, the root main-spar shear strains at the outer station were reduced 30 percent, and the root strains were increased about 40 percent. The outer wing rear-spar shear strains were approximately four times greater with the alleviation system on because of the deflections of the trailing-edge flap.

Horizontal-tail strains.- In order to conserve channels in the recording oscillograph, strain-gage bridges located on the main and rear spars of the horizontal tail were combined electrically to give one output representing horizontal-tail shear and one output representing bending moment. The responses of the combined shear and bending bridges have been analyzed in the same manner as the wing measurements; however, unlike the wing analysis, the results of this analysis refer to the combined effects in main and rear spars. There are indications, based on the calculated standard deviations for the basic and gust-alleviated airplane configurations, that the shear strains at the attachment of the horizontal tail to the fuselage were increased $2\frac{1}{2}$ times with the alleviation controls in operation and that the bending strains were increased $1\frac{1}{2}$ times. Use of the split elevator on the test airplane to reduce pitching in the gust-alleviated configuration, therefore, increases horizontal-tail shear and bending. A histogram of the horizontal-tail shear-strain measurements is shown in figure 8. It should be pointed out that the use of a split elevator in this investigation would not be necessary generally because deflection of the full elevator could accomplish the purpose of alleviating pitching and do so without the large increases in bending strains.

Fatigue life.- The alleviation system installed on the test airplane was designed to improve passenger comfort primarily; still, it would seem desirable to see if the fatigue properties of the wing are modified by the system. It is not possible to arrive at any quantitative evaluation of the fatigue life of the test airplane because of the limited number of bridge locations and strain measurements; however, by use of the strain peaks measured from the records available, it is possible to indicate the strain peaks per mile which the wing main and rear spars experienced in the basic and alleviated configurations. A count was, therefore, made of the strain peaks experienced by the root main-spar shear bridge and root rear-spar shear bridge at the outboard wing reference station, and the results are presented in figure 9.

It can be seen from figure 9(a) that, for turbulence of the intensity encountered during the tests, the root main-spar strain level which is experienced every 1/4 mile in the basic airplane occurs only once every 1/2 mile with the alleviation controls engaged. For the rear spar, however, as indicated in figure 9(b), a strain intensity of 40 units was experienced every mile of flight; whereas with the alleviation system on, this same strain was encountered once every 1/30 mile. A strain intensity of 50 units was not encountered at all with the basic airplane. Thus, the fatigue properties of the rear spar of the wing of an airplane equipped with a gust-alleviation system using trailing-edge wing flaps could become an important consideration in the estimation of airplane life.

Pull-Up Maneuvers

Strain measurements obtained in the pull-up maneuvers have been converted to aerodynamic shear, bending moment, and torque by combining various strain-gage outputs in a manner determined during a loading calibration. Time histories of the loads thus determined and other pertinent quantities measured in a pull-up with the basic airplane are presented in figure 10; and, for comparison, time variations of the same quantities with the gust-alleviation system in operation are presented in figure 11.

For the basic airplane, a pull-up to approximately 2g was made from steady flight at an altitude of 5,000 feet and a true airspeed of 130 knots and, with the alleviated airplane, a pull-up to 1.7g was made at the same speed and altitude. Differences in the wing and tail loads and airplane motions which are readily apparent in the time histories are, therefore, due to the gust-alleviation controls. In order to examine in more detail the effects of the operation of the controls, aerodynamic lift, bending moment, and torque shown in figures 10 and 11 at two stations on the right wing are replotted in figures 12 and 13 to show variations with airplane normal acceleration.

Loads at wing root.- As would be expected for the basic airplane, shear, bending moment, and torque at the wing root vary linearly with airplane normal acceleration in the pull-up maneuver as shown in figure 12. In the case of the pull-up with the gust-alleviation system in operation, it can be seen (fig. 13) that the shear, bending moment, and torque at the wing root do not vary linearly with normal acceleration since they are influenced by flap deflection as well. In order to evaluate the loads resulting from deflecting the flap with constant normal acceleration, the following relationships between normal acceleration, flap deflection, and loads were written:

$$\begin{Bmatrix} \Delta G_{WR} \\ \\ \Delta M_{WR} \\ \\ \Delta Q_{WR} \end{Bmatrix} = \Delta a_n \begin{Bmatrix} \dfrac{\partial G_{WR}}{\partial a_n} \\ \\ \dfrac{\partial M_{WR}}{\partial a_n} \\ \\ \dfrac{\partial Q_{WR}}{\partial a_n} \end{Bmatrix} + \Delta \delta_f \begin{Bmatrix} \dfrac{\partial G_{WR}}{\partial \delta_f} \\ \\ \dfrac{\partial M_{WR}}{\partial \delta_f} \\ \\ \dfrac{\partial Q_{WR}}{\partial \delta_f} \end{Bmatrix} \tag{1}$$

For this evaluation, the quantities ΔG_{WR}, ΔM_{WR}, ΔQ_{WR}, Δa_n, and $\Delta \delta_f$ were obtained from the time-history records at each 1/10-second interval (with 22 points in all); the aforementioned three equations were solved by the least-squares method to obtain the contribution of the normal acceleration $\frac{\partial(\ )}{\partial a_n}$ and wing-flap deflection $\frac{\partial(\ )}{\partial \delta_f}$ to the wing root shear ΔG_{WR}, root bending moment ΔM_{WR}, and torque about the torque reference axis ΔQ_{WR}.

Numerical results from the procedure just outlined are summarized in the following table:

Load	Basic airplane	With gust-alleviation system on -	
		$\frac{\partial(\ )}{\partial a_n}$	$\frac{\partial(\ )}{\partial \delta_f}$
Shear	3,550 $\frac{lb}{g}$	3,528 $\frac{lb}{g}$ . . . . . . (e_s = 10)	41 $\frac{lb}{deg}$ . . . . (e_s = 1)
Bending moment . . .	395,000 $\frac{in\text{-}lb}{g}$	395,170 $\frac{in\text{-}lb}{g}$ . . . (e_s = 5,800)	4,580 $\frac{in\text{-}lb}{deg}$ . . . . . (e_s = 380)
Torque	-83,000 $\frac{in\text{-}lb}{g}$	-82,960 $\frac{in\text{-}lb}{g}$, . . (e_s = 2,160)	-2,045 $\frac{in\text{-}lb}{deg}$ . . . . (e_s = 140)

It can be seen from the preceding table that the values of the loads due to changing normal acceleration with flaps held constant as determined from the least-squares solution of equation (1) are consistent with the results obtained directly from the basic-airplane data where flaps were actually neutral. The least-squares results are accompanied in the aforementioned table by the standard error of estimate for each coefficient (ref. 3). The values given for the basic airplane were obtained from the variation of shear, moment, and torque with normal acceleration shown in figure 12. The increase in bending moment due to flap deflection is indicative of the bending-moment alleviation which can be expected when the flaps act to relieve the wing airloads in response to signals from the angle-of-attack vane in rough air. The increase in torque in the pull-up maneuver, due to the rearward shift in the chordwise center of load with flap deflection, shows that the rear spar of the wing carries a greater proportion of the airload with the alleviation system in operation.

Loads at outboard station.- A second strain-gage station was located on the right wing at approximately 39 percent of the semispan outboard of the airplane center line. The strain-gage bridges at this station were calibrated to give a measure of the shear, bending moment, and torque outboard of the station. Variations with normal acceleration of the shear and bending moment at this station for the basic airplane in a pull-up maneuver are shown in figure 12 and for the airplane with alleviation controls operating are shown in figure 13. Torque measurements were not available for these tests.

From an analysis similar to that just outlined for the wing's root loads, the following loads for the basic airplane and for the gust-alleviation system on were obtained:

Load	Basic airplane	With gust-alleviation system on -	
		$\frac{\partial(\ )}{\partial a_n}$	$\frac{\partial(\ )}{\partial \delta_f}$
Shear	2,280 $\frac{\text{lb}}{g}$	2,270 $\frac{\text{lb}}{g}$ . . . . . . (e_s = 21)	37 $\frac{\text{lb}}{\text{deg}}$ . . . . (e_s = 1)
Bending moment . . .	160,000 $\frac{\text{in-lb}}{g}$	170,700 $\frac{\text{in-lb}}{g}$ . . . (e_s = 1,900)	2,380 $\frac{\text{in-lb}}{\text{deg}}$ . . . . . (e_s = 130)

Horizontal-tail loads.- The strain-gage reference stations for the measurement of shear and bending moment on the horizontal tail are located just outboard of the attachment of the tail to the fuselage. The aerodynamic loads measured outboard of the strain-gage reference on the right side of the tail have been analyzed to determine the loads imposed by the operation of the gust-alleviation-system controls (auxiliary elevators). For the basic airplane, the tail loads on the right horizontal tail ΔG_{TR} can be considered as being the result of the tail angle of attack and the elevator deflection, so that

$$\Delta G_{TR} = \frac{\partial G_{TR}}{\partial \alpha_t} \Delta \alpha_t + \frac{\partial G_{TR}}{\partial \delta_e} \Delta \delta_e \tag{2}$$

and

$$\Delta \alpha_t \cong \left(1 - \frac{d\epsilon}{d\alpha}\right) \Delta \alpha_V' + \frac{l_t}{V} \Delta \dot{\theta} \tag{3}$$

Measurements of G_{TR}, α_V', $\dot{\theta}$, δ_e, and V are available in time-history form for a pull-up maneuver (fig. 10) where l_t is the distance from the center of gravity to the quarter chord of the horizontal tail, 22.5 feet, and $d\epsilon/d\alpha$ is assumed to be 0.5. Data were obtained from the time histories at 1/10-second intervals and were substituted in equation (2). As before, a solution by the least-squares method yielded the desired load coefficients $\frac{\partial G_{TR}}{\partial \alpha_t}$ because of tail angle of attack and $\frac{\partial G_{TR}}{\partial \delta_e}$ because of elevator deflection.

With the gust-alleviation system in operation, the auxiliary elevator motion also influences the tail load and, therefore, in this case the corresponding equation is

$$\Delta G_{TR} = \frac{\partial G_{TR}}{\partial \alpha_t} \Delta \alpha_t + \frac{\partial G_{TR}}{\partial \delta_e} \Delta \delta_e + \frac{\partial G_{TR}}{\partial \delta_{e,aux}} \Delta \delta_{e,aux} \tag{4}$$

Solution of the tail load parameters with data from the time histories substituted into equations (2) and (4) gave the results which are shown in the following table:

Tail load parameter, lb/deg	Basic airplane	With gust-alleviation system on -
$\partial G_{TR}/\partial \alpha_t$	81	84 . . . . ($e_s = 6$)
$\partial G_{TR}/\partial \delta_e$	12	10 . . . . ($e_s = 2$)
$\partial G_{TR}/\partial \delta_{e,aux}$	--	27 . . . . ($e_s = 1$)

The similarity of the calculated load coefficients due to tail angle of attack for the basic and gust-alleviated airplane configurations indicates that flow conditions at the tail are only slightly changed by operation of the gust-alleviation flaps on the wing. The auxiliary elevator, then, is the main contributor to the increased load on the horizontal tail as shown in figure 11 for the gust-alleviated airplane.

CONCLUDING REMARKS

Results from an analysis of a sample of the measurements of wing and tail loads and spar strains associated with the operation of a gust-alleviation system on a modified twin-engine light transport airplane in rough air indicate that, for a reduction in airplane normal acceleration of 43 percent, based on root-mean-square values, wing main-spar bending strains were also reduced; whereas shear strains in both the main and rear spars of the wing were increased. The increases in main-spar shear result from the fact that the test-airplane wing was essentially of single-spar construction which required some of the shear introduced by motion of the trailing-edge wing flaps to be transferred to the main spar.

Horizontal-tail shear and bending strains were increased because of operation of the split elevator on the gust-alleviated airplane.

Increases in the magnitude and frequency of occurrence of some of the strains in the wing and tail structure in rough air associated with operation of the gust-alleviation controls indicate that fatigue would be an important consideration in designs utilizing this type of gust-alleviation system.

The reduction in normal acceleration indicated by these initial results is not necessarily the optimum alleviation which can be obtained with the present system, and any further reductions in accelerations would be expected to be accompanied by changes in the magnitude of the loads and strains experienced.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., May 29, 1956.

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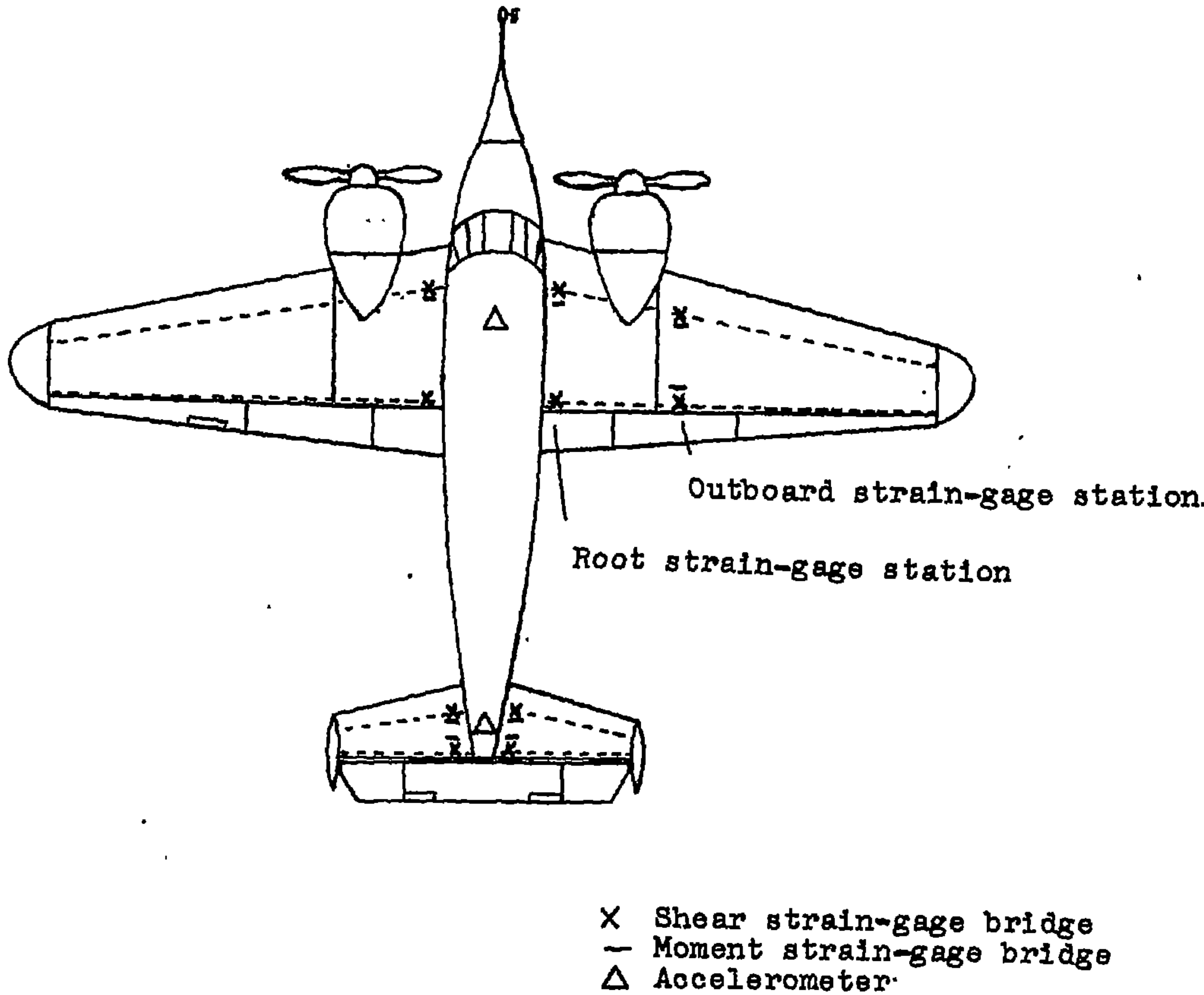


Figure 1.- Plan form of test airplane showing strain-gage and accelerometer locations.

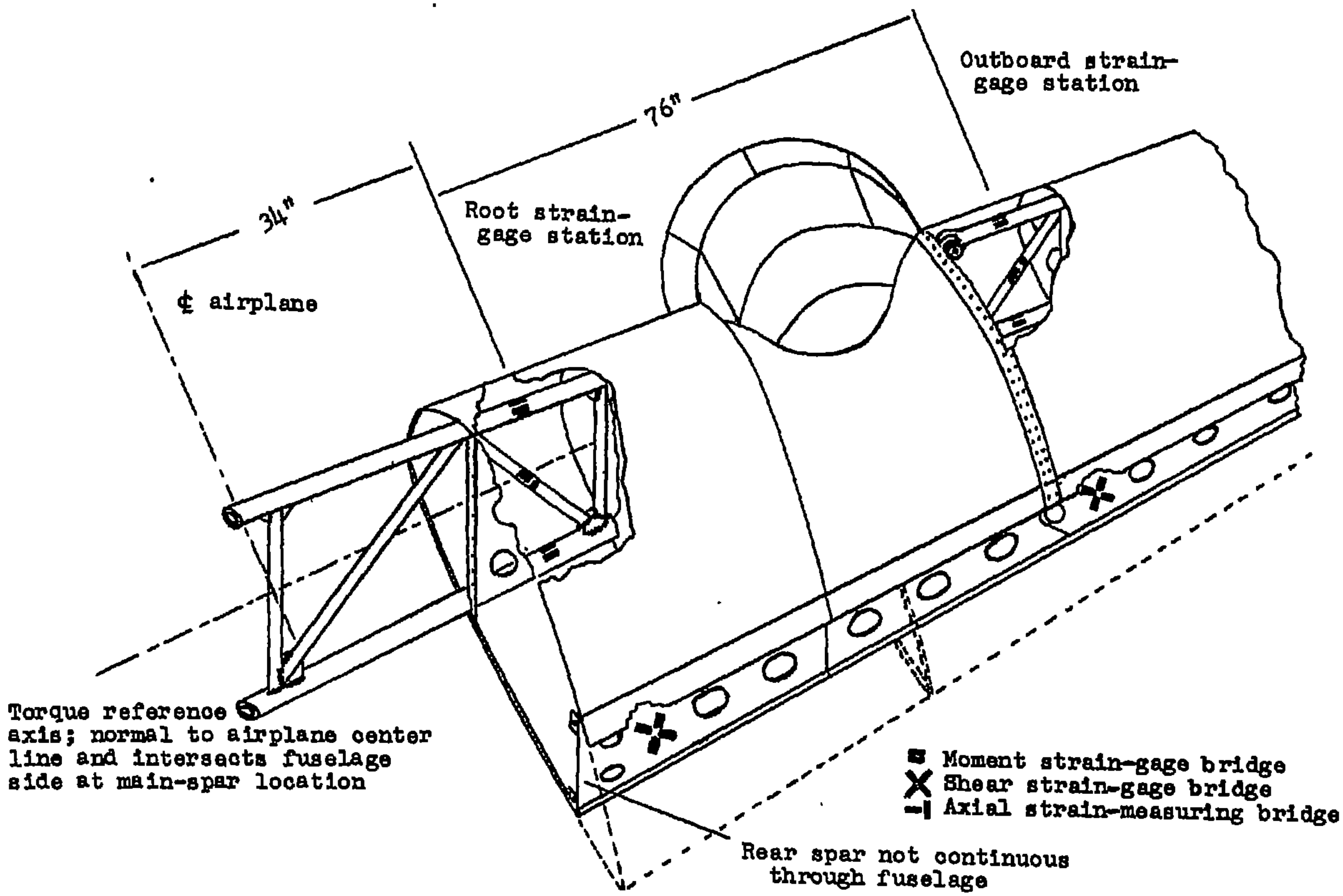
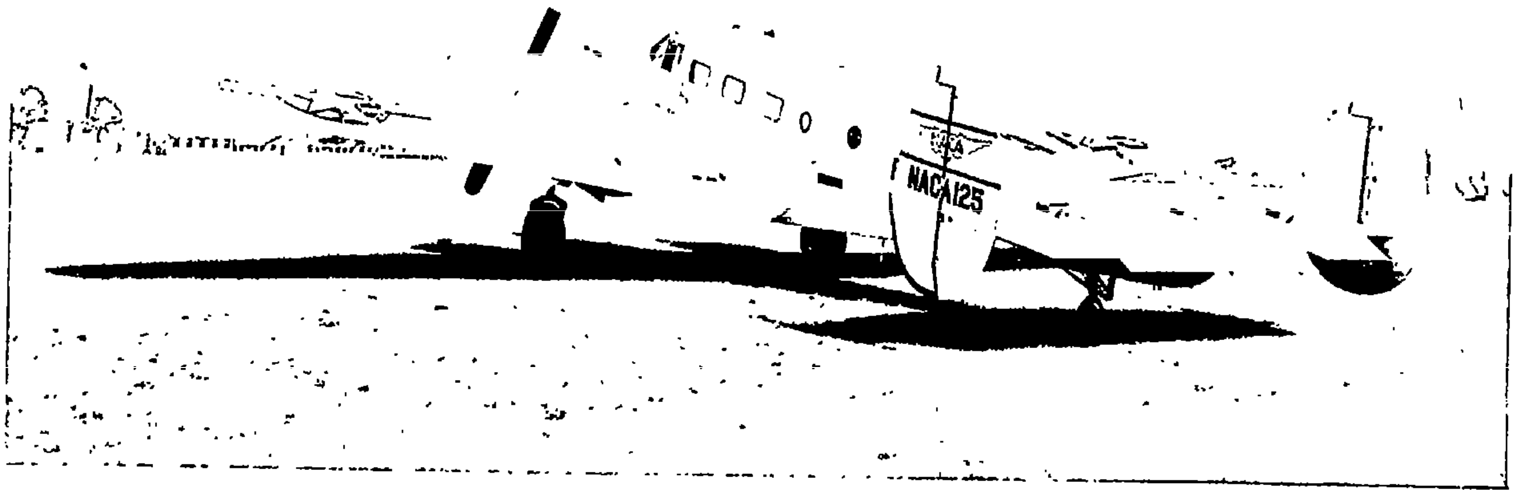
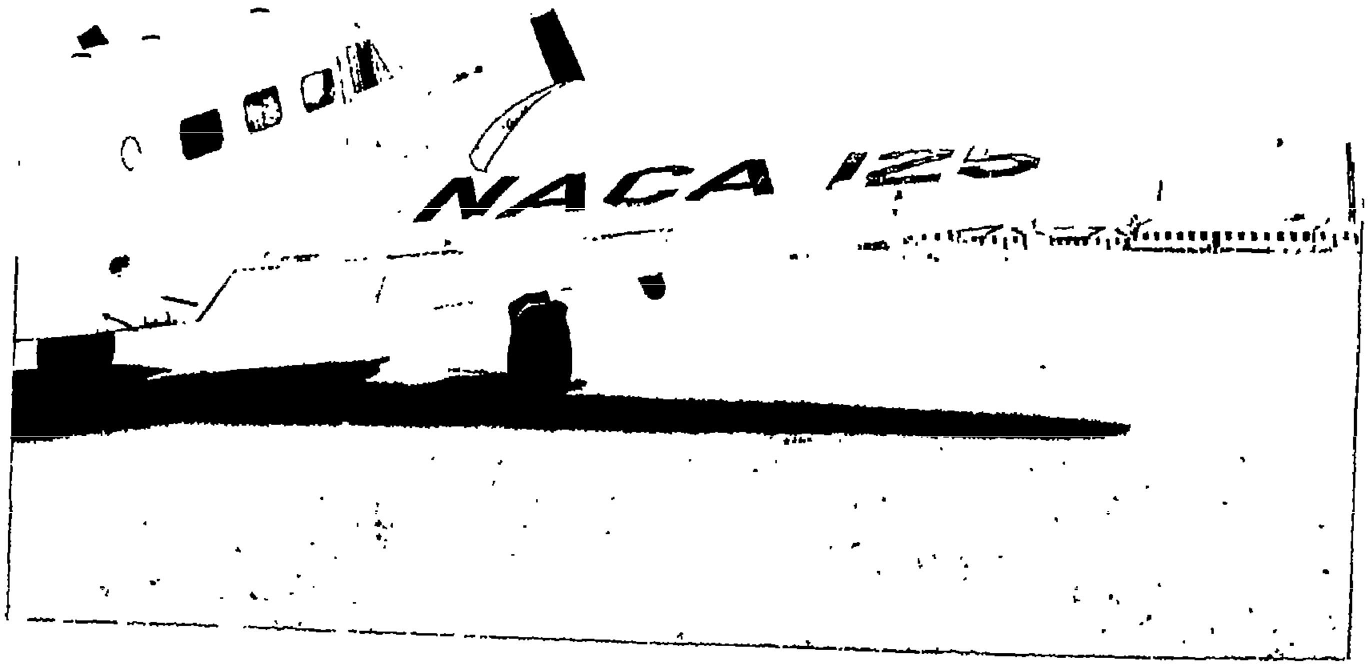


Figure 2.- Wing of test airplane showing some structural details and the locations of the strain-gage bridges.



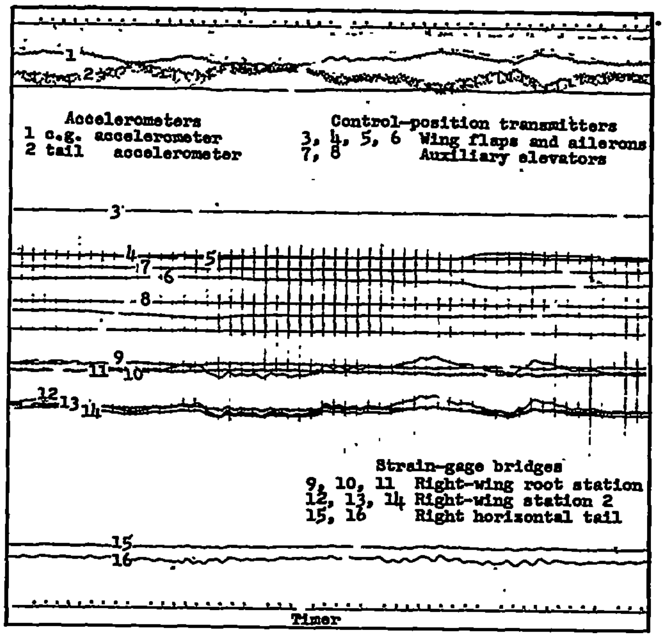
(a) Three-quarter view of airplane showing various control surfaces. L-88852

Figure 3.- Photograph of test airplane.

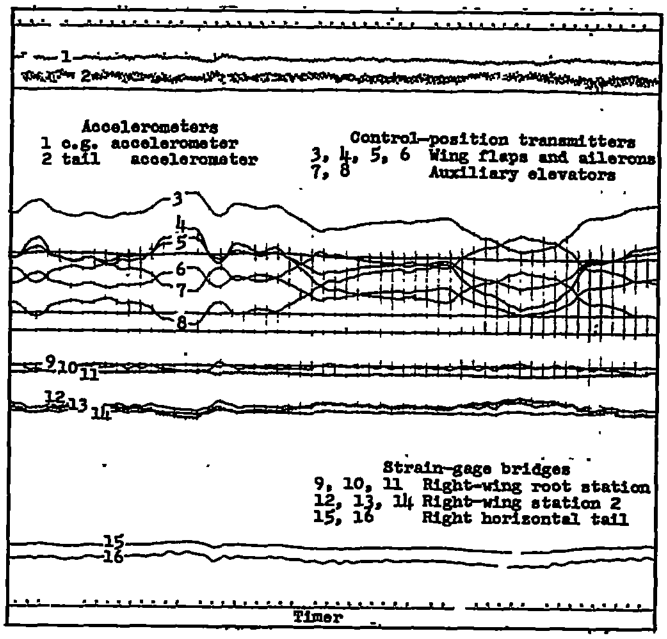


(b) Gust-alleviation flap control in the deflected position. L-88847

Figure 3.- Concluded.



(a) Basic airplane with no alleviation.



(b) Airplane with alleviation system in operation.

Figure 4.- Typical oscillogram of strain-gage response, accelerometers, and control positions of test airplane flying in turbulence.

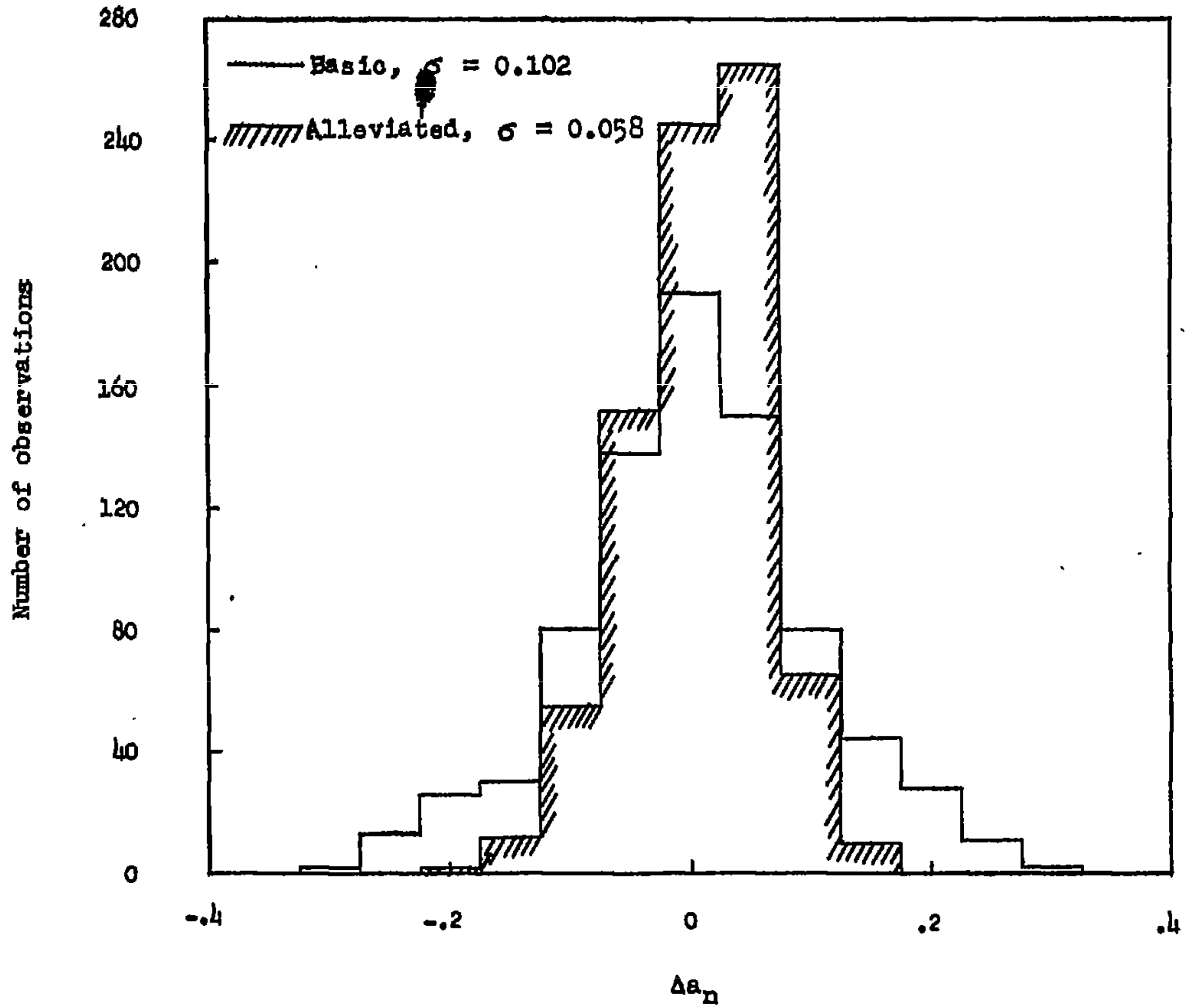


Figure 5.- Comparison of normal acceleration measured at center of gravity of airplane in rough air with gust-alleviation system on and off.

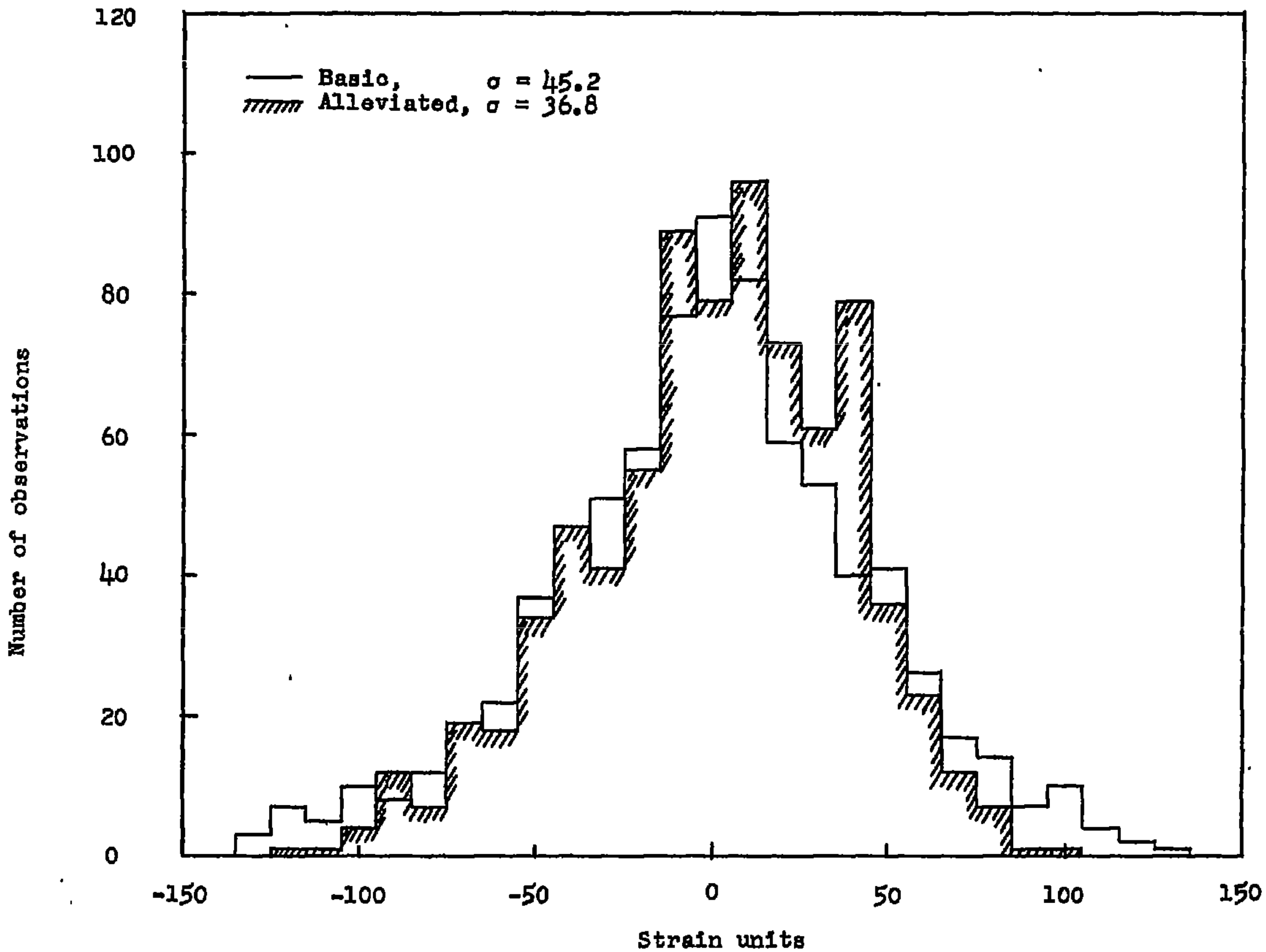
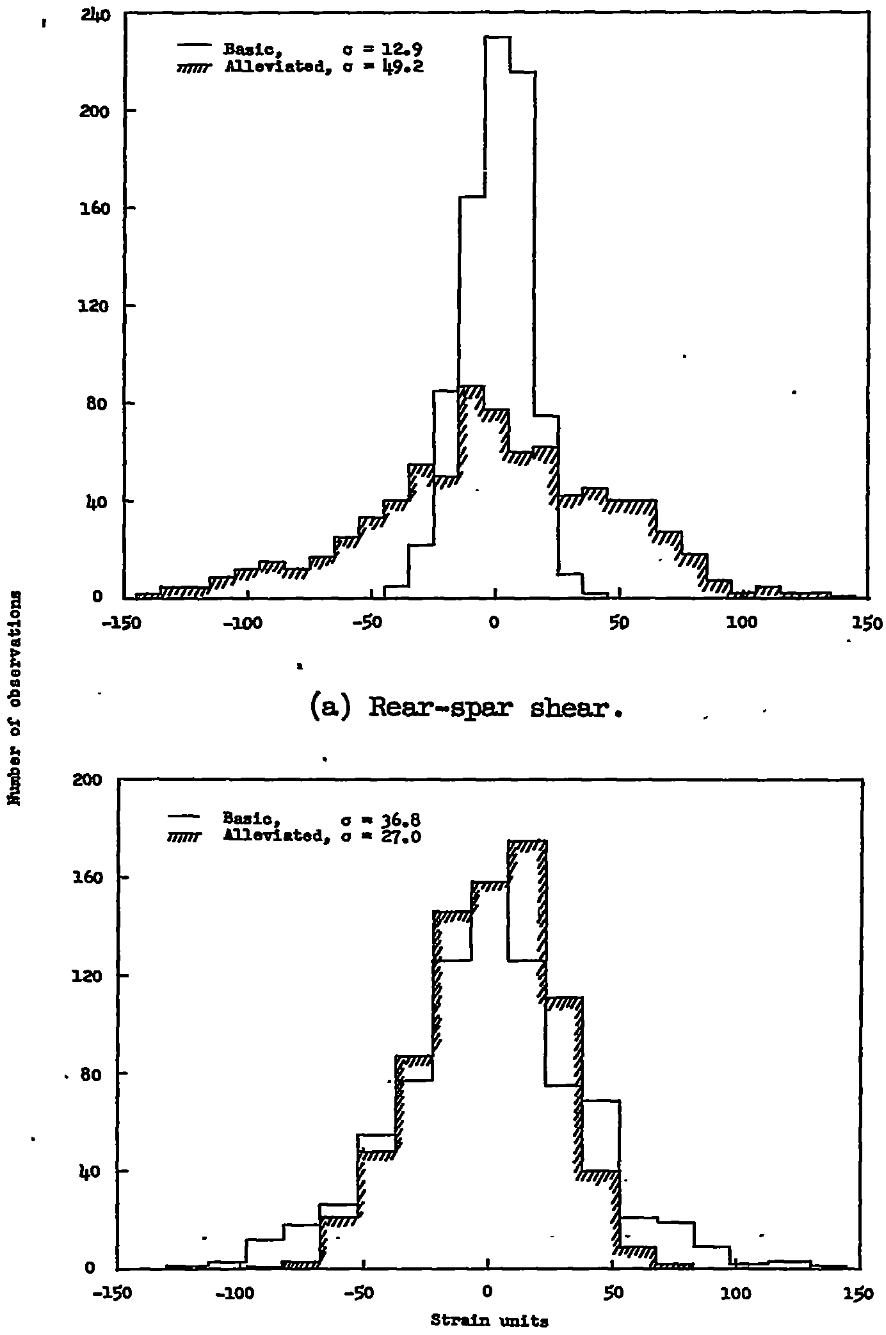


Figure 6.- Comparison of wing-root bending strains measured in rough air with gust-alleviation system on and off.



(a) Rear-spar shear.

(b) Main-spar shear.

Figure 7.- Comparison of strains measured at wing outer station in rough air with gust-alleviation system on and off.

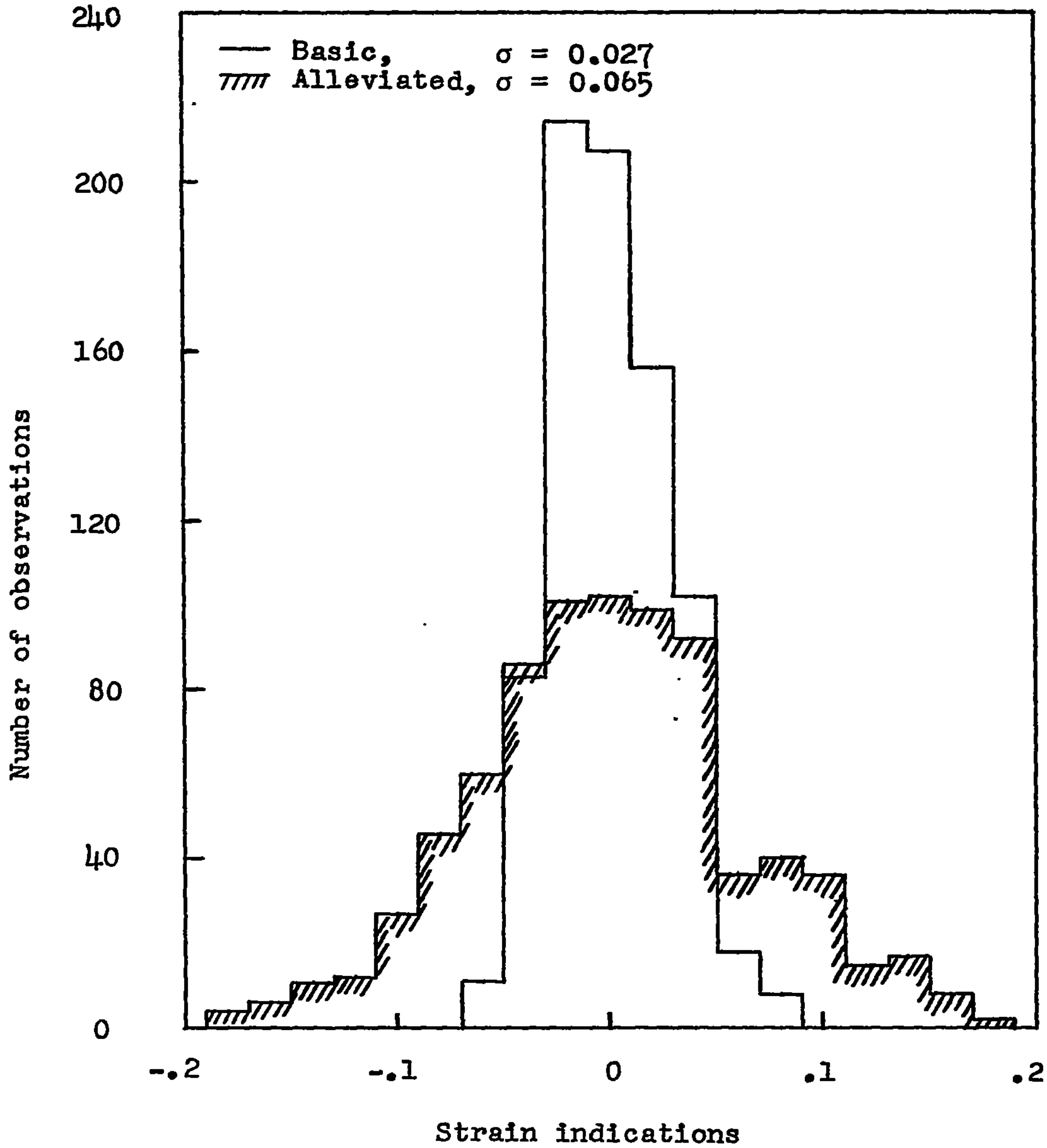
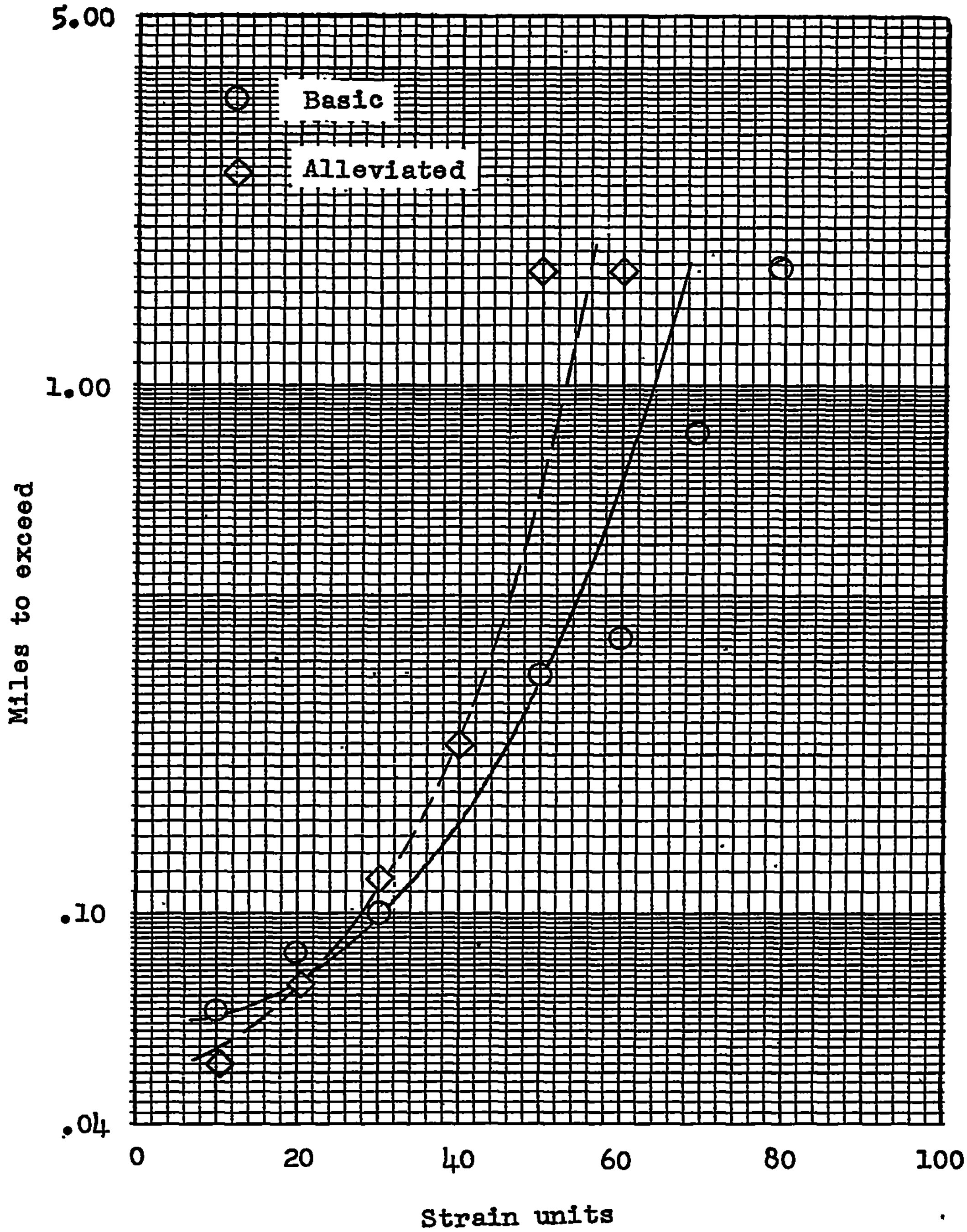
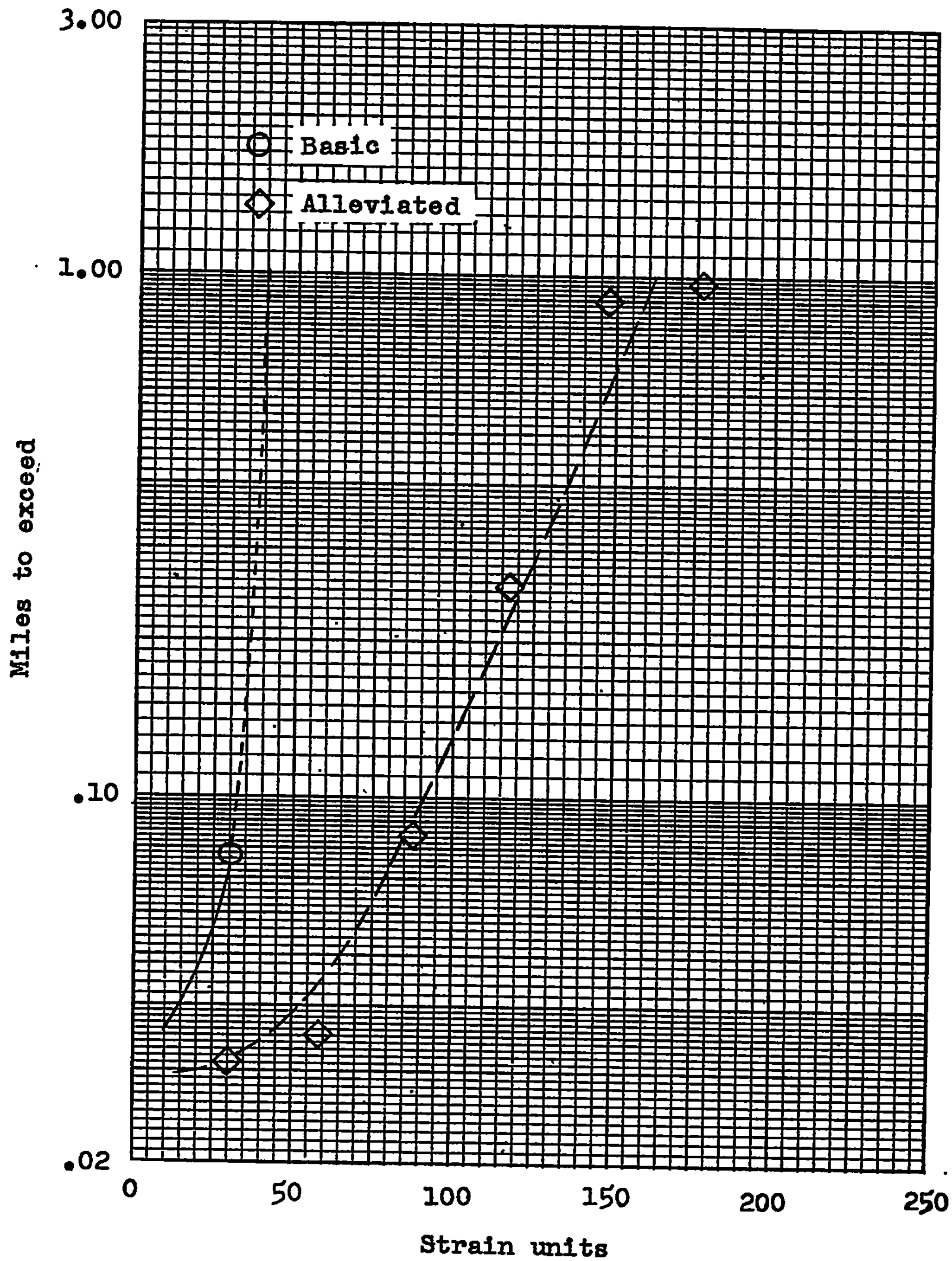


Figure 8.- Comparison of horizontal-tail shear-strain indications measured in rough air with gust-alleviation system on and off.



(a) Wing main spar with alleviation system on and off for the turbulence intensity encountered.

Figure 9.- Flight miles required to exceed a given shear-strain level.



(b) Wing rear spar with alleviation system on and off for the turbulence intensity encountered.

Figure 9.- Concluded.

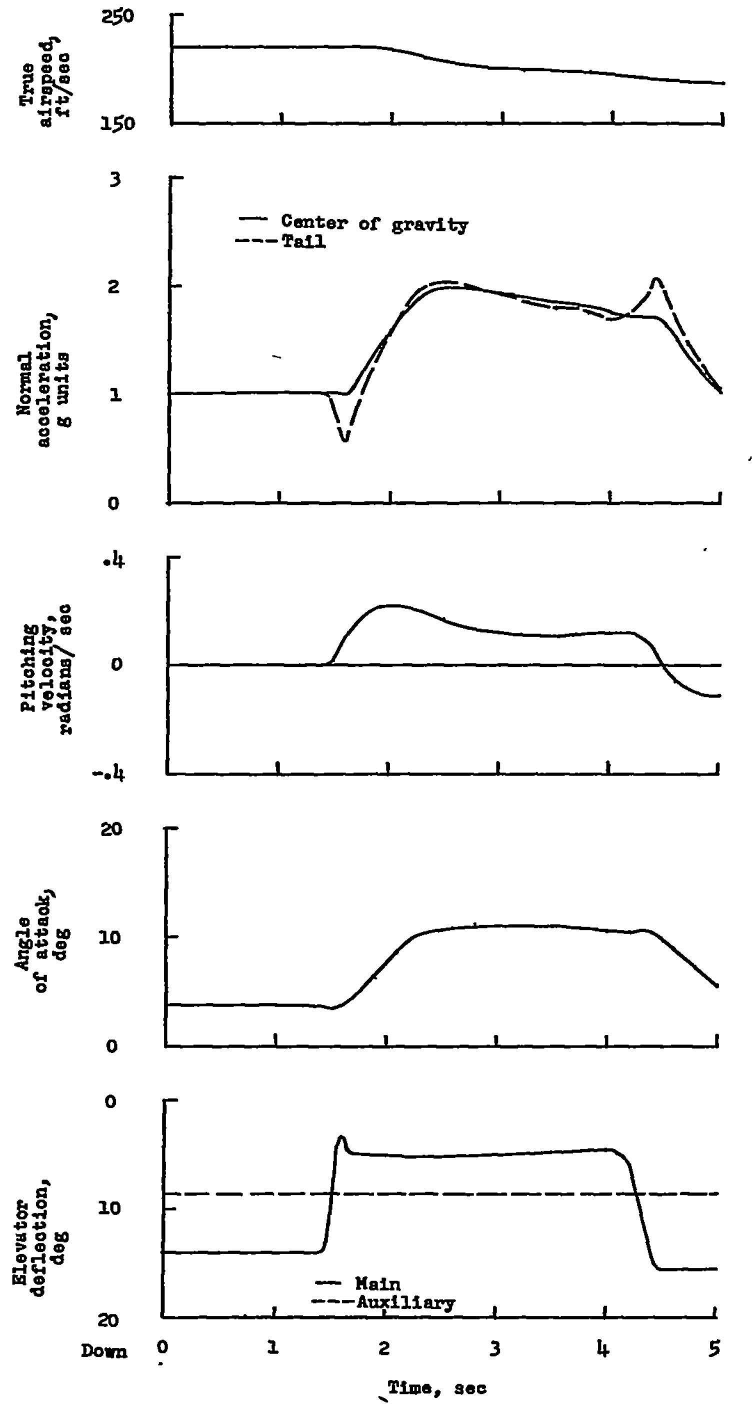


Figure 10.- Time history of airplane motions, wing loads, and tail loads in a pull-up with the basic airplane.

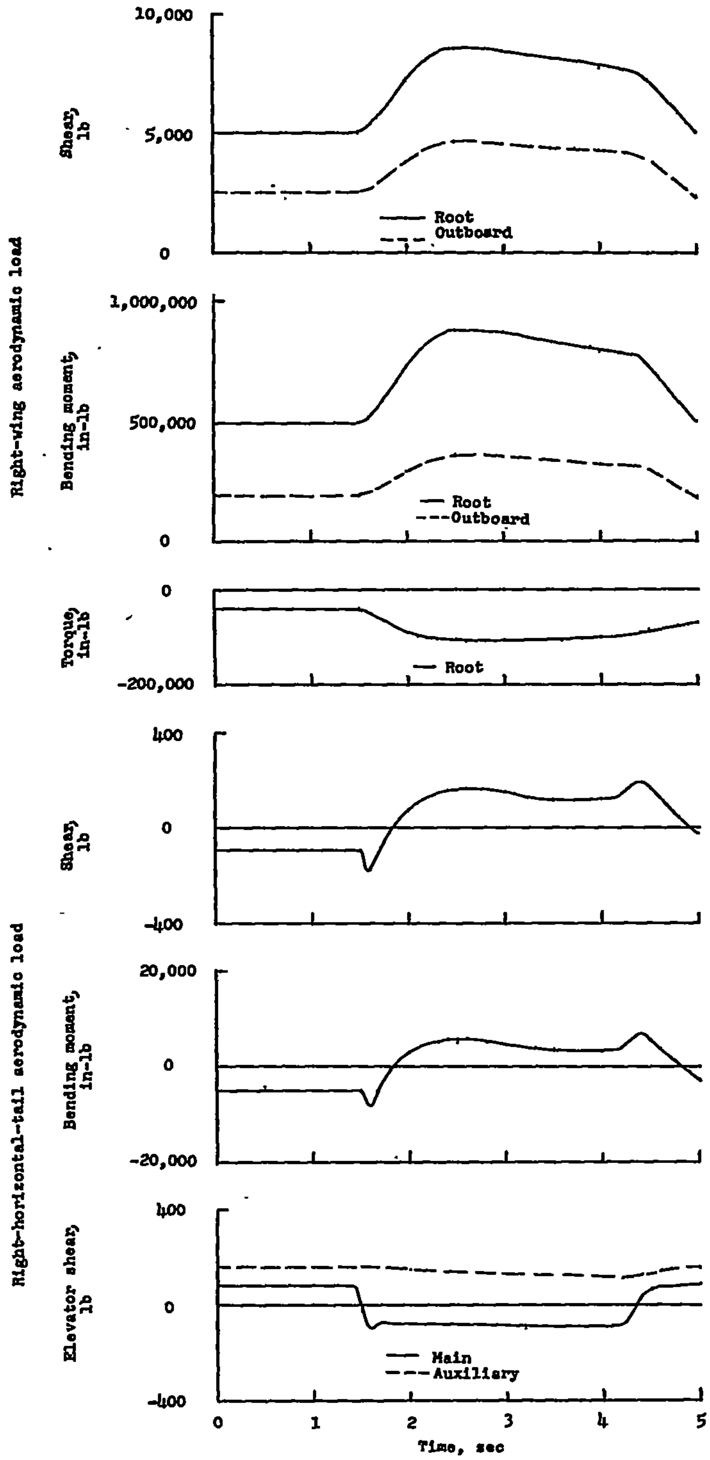


Figure 10.- Concluded.

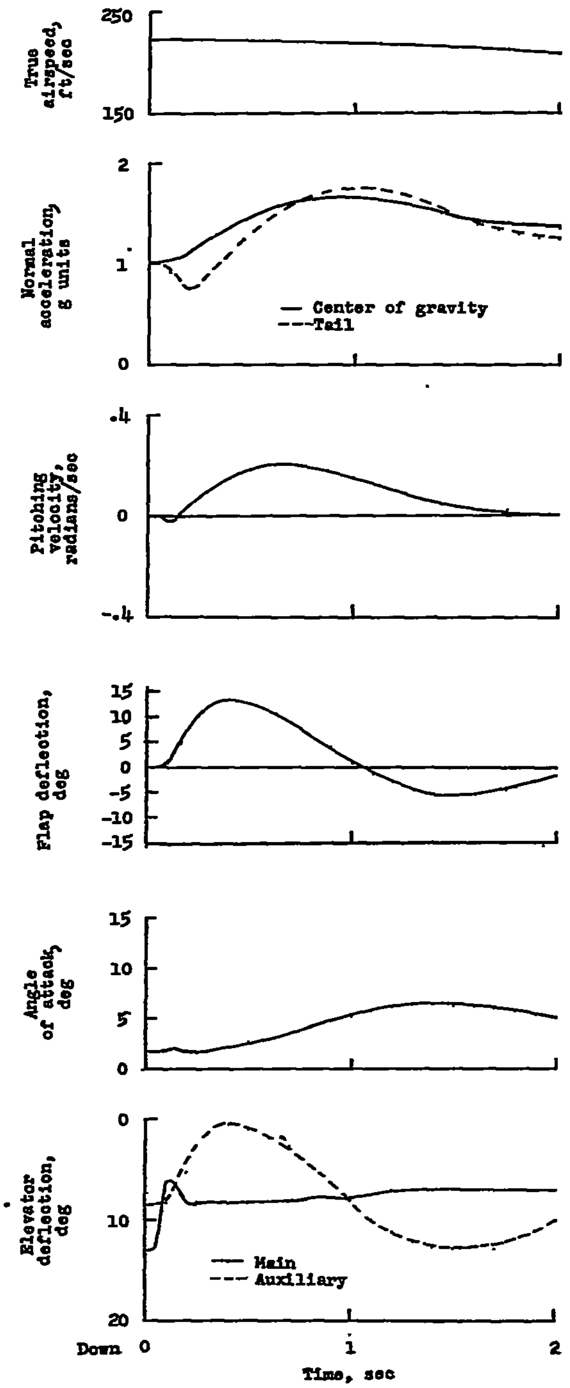


Figure 11.- Time history of airplane motions, wing loads, and tail loads in a pull-up maneuver with gust-alleviation system in operation.

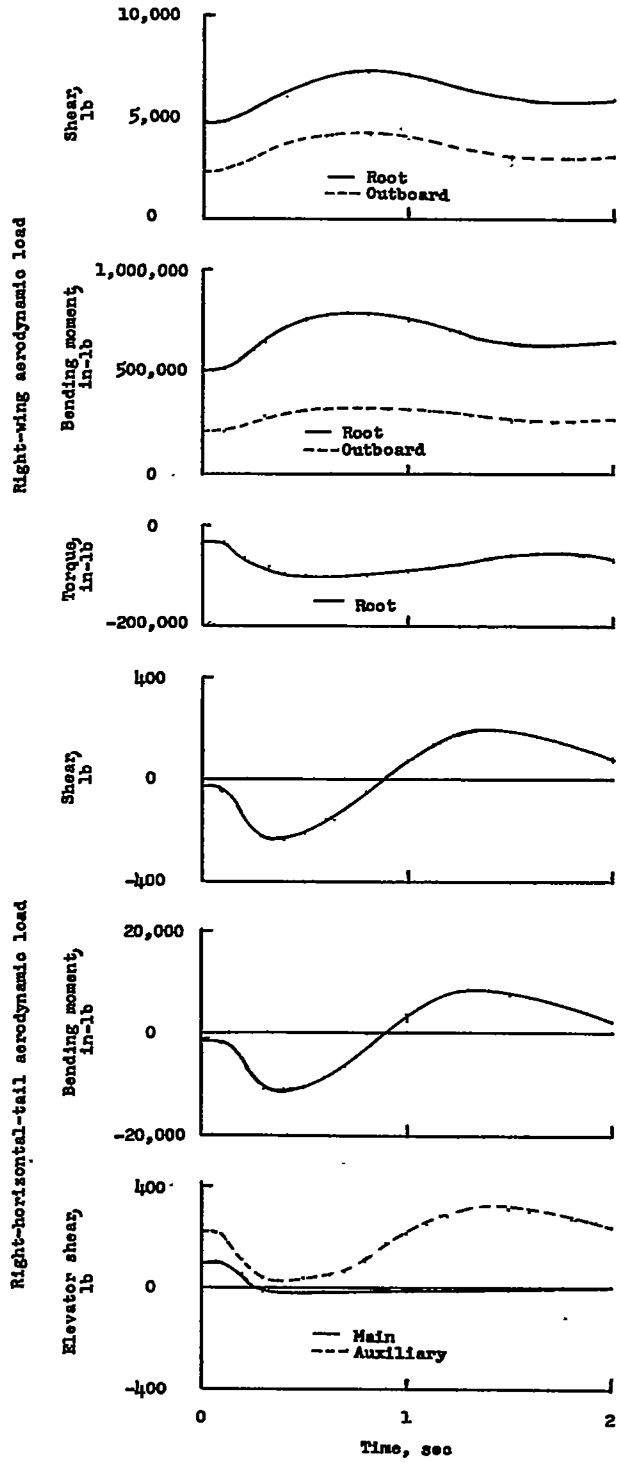


Figure 11.- Concluded.

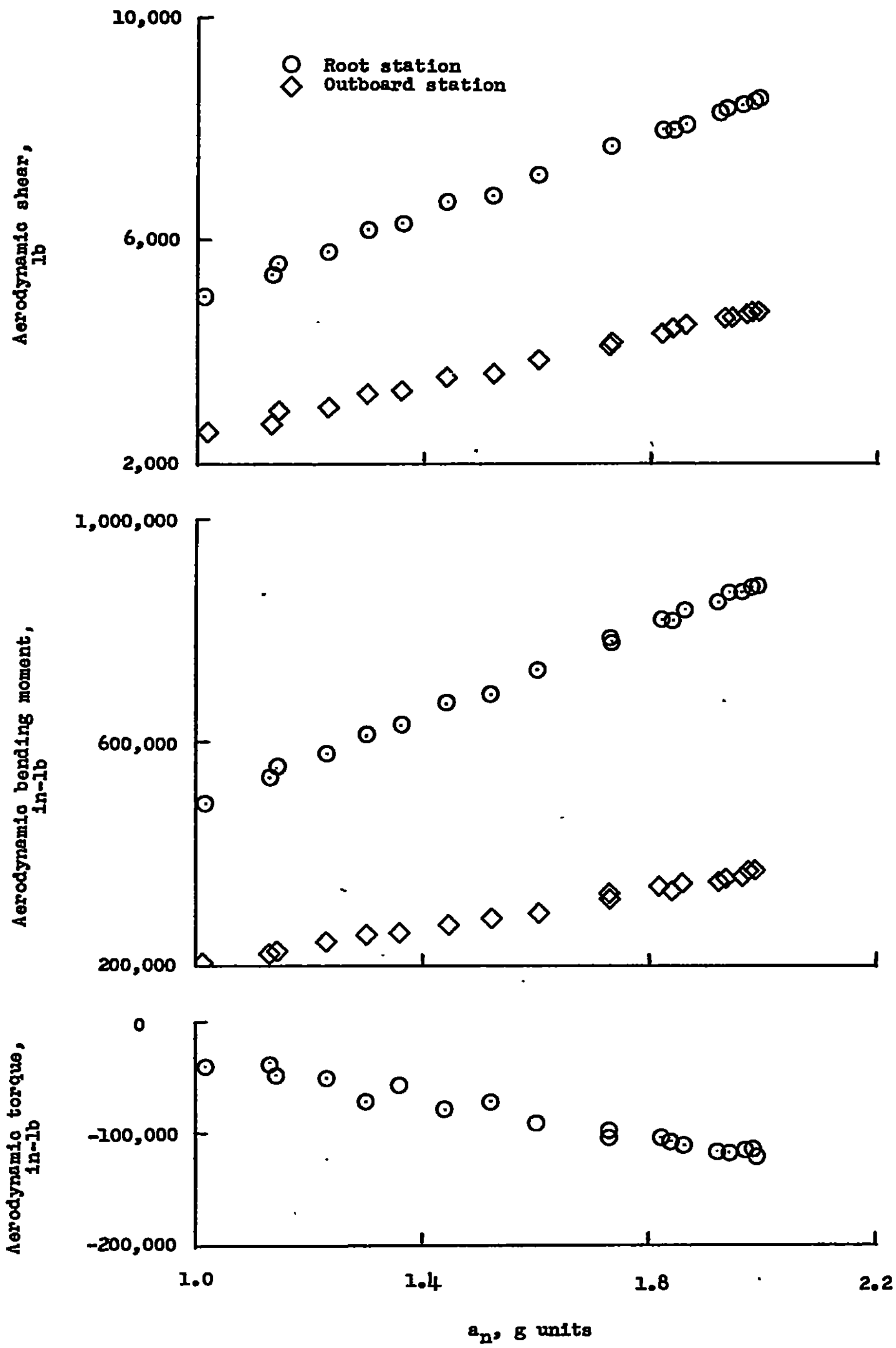


Figure 12.- Variation with center-of-gravity normal acceleration of the aerodynamic loads on the right wing in a pull-up maneuver with basic airplane.

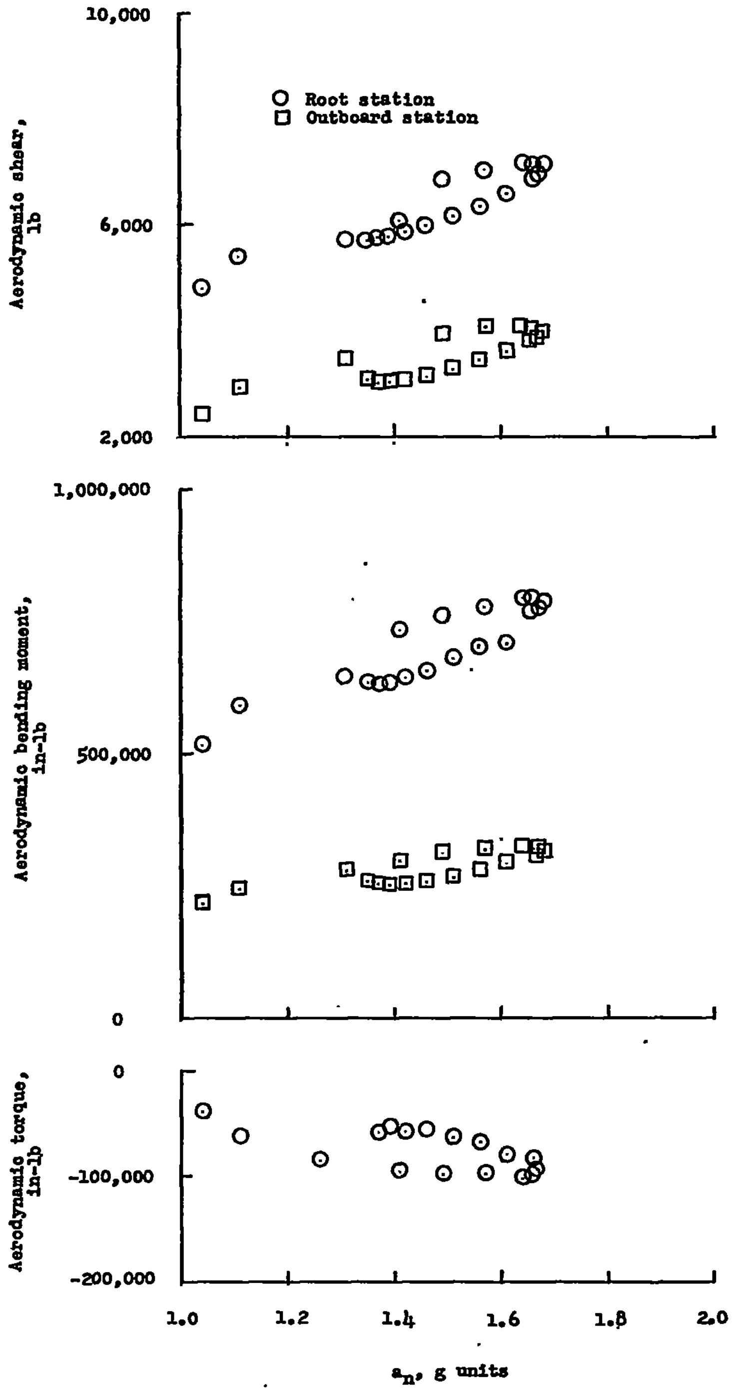


Figure 13.- Variation with center-of-gravity normal acceleration of the aerodynamic loads on the right wing in a pull-up maneuver with the gust-alleviation system in operation.